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Woodland Volume Equations for Arizona Fort Apache and San Carlos Indian Reservations[1]

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ABSTRACT

Volume prediction equations were developed for oak, juniper, and pinyon trees on the Fort Apache and San Carlos Indian Reservations in Arizona. The equations require as inputs total height and tree diameter measurements. Results are presented in equation and tabular formats. Volume equation construction and equation comparisons are discussed.

KEYWORDS: *Pinus edulis, Juniperus osteosperma, J. monosperma, J. deppeana, J. scopulorum, Quercus arizonica, Q. emoryi, Q. chrysolepis, Q. gambelii*, volume table

INTRODUCTION

Evergreen woodlands composed of oak, juniper, and pinyon dominate a large portion of the Fort Apache and San Carlos Indian Reservations. These woodlands lie in the extreme northern edge of a vegetation type shaped by mild winters and wet summers. This vegetation type, known by Shreve's (1915) Spanish term "encinal," is centered in the Sierra Madre of Mexico, extends northward to Arizona's Mogollon Rim, into southwestern New Mexico, and to Trans-Pecos Texas (Brown 1982).

Fort Apache and San Carlos tribes want to manage their portion of the encinal to ensure a continuing supply of firewood and other wood products, wildlife habitat, livestock forage, and other benefits. To provide current woodland management information, the San Carlos Reservation was inventoried in 1981 (USDA FS 1982) and the Fort Apache Reservation was inventoried in 1986 (USDA FS 1986). Estimation of total wood volume was a primary objective of these inventories. Because direct volume measurement is time-consuming and costly, data were collected in these inventories on a subsample of trees for subsequent volume equation development. This paper reports on equation construction from these data.

FIELD MEASUREMENTS

Volume data were collected from 66 plots on the Fort Apache Reservation and from 101 plots on the San Carlos Reservation (fig. 1). The Bureau of Indian Affairs and San Carlos Tribal forestry staff collected the data. For each Fort Apache plot, up to three trees were randomly selected from each of three diameter classes, 3.0 to 9.9, 10 to 17.9, and >18 inches diameter at root collar (DRC). For each

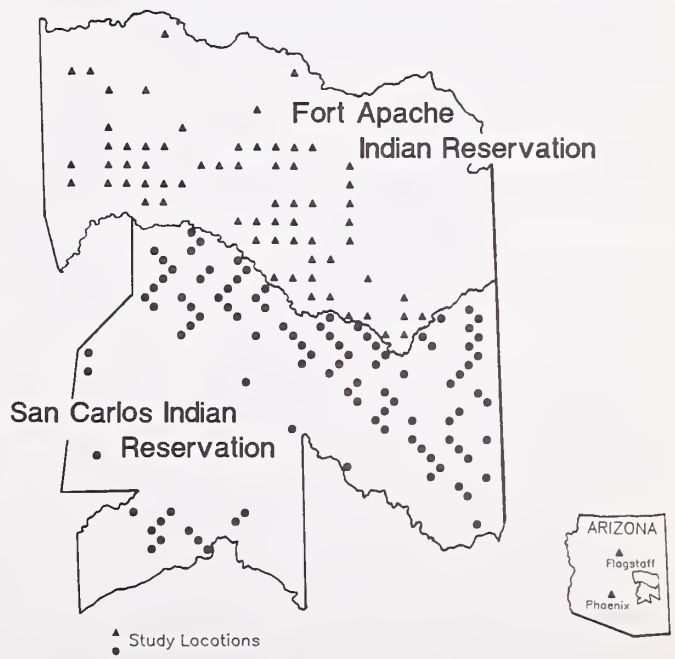

Figure 1—Map of 66 Fort Apache and 101 San Carlos study plots.

[1]This study was a cooperative effort between the Intermountain Research Station, the San Carlos Apache Tribe, and the Bureau of Indian Affairs San Carlos and Fort Apache Agencies, who collected the field data.

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San Carlos plot, up to three trees per pinyon, juniper, and oak genus were randomly selected from each diameter class described above.

Volume estimation was done using visual segmentation, a method of counting the numbers of wood segments by size class within a tree (Born and Chojnacky 1985). Wood segments were determined by dividing tree stems and branches into 1- to 6-foot long sections using 2-inch diameter classes. Cubic foot volume was computed for each segment using Huber's log formula (Husch and others 1982, p. 101). For each tree, segments that included wood and bark of all live and dead stems and branches larger than 1.5 inches in diameter were summed into a gross cubic foot volume.

Other tree variables measured for volume equation development were total height, DRC, and number of basal stems. For trees forking at the root collar, DRC was calculated from measurements of all basal stems combined:

$$\text{DRC} = \sqrt{\sum_{i=1}^{n} D_i^{\,2}} \qquad (1)$$

where

D_i = basal diameter of each stem

n = number of basal stems 1.5 inches or larger.

Species sampled were pinyon (*Pinus edulis* Engelm.), Utah juniper (*Juniperus osteosperma* [Torr.] Little), oneseed juniper (*J. monosperma* [Engelm.] Sarg.), alligator juniper (*J. deppeana* Steud.), Rocky Mountain juniper (*J. scopulorum* Sarg.), Arizona white oak (*Quercus arizonica* Sarg.), Emory oak (*Q. emoryi* Torr.), canyon live oak (*Q. chrysolepis* Liebm.), and Gambel oak (*Q. gambelii* Nutt.).

ANALYSIS AND MODELING

I used three assumptions based on my previous woodland volume modeling experience (Chojnacky 1985; Chojnacky and Ott 1986) to guide this analysis.

Assumption 1—Volume is best predicted from a combination variable, DRC squared times height (DSQH).

Assumption 2—The volume to DSQH relationship differs slightly between small and large trees for a given species.

Assumption 3—The volume to DSQH relationship differs between single-stem and multiple-stem trees for a given species.

These assumptions were not subjected to rigorous statistical tests because some inconsistencies in visual segmentation application showed up in the data edit. These inconsistencies probably inflated individual tree volume variations, thus confounding measurement error with sampling error. Resulting hypothesis tests would be misleading unless the unknown visual segmentation inconsistencies were taken into account. Instead, the three modeling assumptions were examined graphically to identify data trends and potential outlying data problems.

But before graphical analyses were done, the combined effect of tree form and measurement differences between Fort Apache and San Carlos data was tested. In this test between reservations, I grouped the data by genus and tree-size class. I determined two tree-size classes by separating small trees with a DSQH of 5,000 or less from larger trees with a DSQH greater than 5,000. A DSQH of 5,000 roughly corresponded to trees with a 15- to 17-inch DRC.

For each size class of each genus, separate reservation volume equations were tested against a single combined volume equation (Chojnacky 1985, p. 5; Graybill 1976, p. 247). Tests for all equations except the small size (DSQH ≤ 5,000) oak equations showed no significant difference between reservations (F-test P-values were larger than 0.1). An additional graphical comparison between the Fort Apache and San Carlos small oak data showed that the statistical difference was probably influenced by several "outlying" San Carlos data points. Because these points were later found to be in error, analysis proceeded assuming no differences between Fort Apache and San Carlos data.

Graphical analysis showed the three underlying analysis assumptions were reasonable. The combination variable, DSQH, was clearly correlated with volume. The volume-to-DSQH relationship appeared different between small and large trees. Also, it seemed reasonable to use a DSQH of 5,000 as the breakpoint between large and small trees. Finally, the graphs showed less volume for multiple-stem trees than for single-stem trees with the same DSQH. But multiple-stem and single-stem pinyon were combined because the data included only two multiple-stem pinyon.

Graphics were also used to determine the number of species-specific juniper and oak equations to construct. I grouped data by genus and found no clear evidence for further separation of the genus groups into species groups. When differences were apparent (for instance, the few oneseed juniper shown in figure 2), species separations were not justifiable because of small sample sizes.

Therefore, data were grouped into the following five categories for parameter estimation:

1. Multiple-stem juniper
2. Single-stem juniper
3. Multiple-stem oak
4. Single-stem oak
5. Multiple/single-stem pinyon.

I used a volume model from my previous work with the Hualapai and Havasupai Indian Reservations:

$$V = \begin{cases} \beta_0 + \beta_1 X + \beta_2 X^2 & \text{for } X \le X_0 \\ \beta_3 + \beta_1 X + \beta_4 / X & \text{for } X > X_0 \end{cases} \qquad (2)$$

where

V = gross cubic foot volume of wood and bark from all stems and branches larger than 1.5 inches in diameter

X = DSQH divided by 1,000

β_i = parameters estimated from data

X_0 = 5.

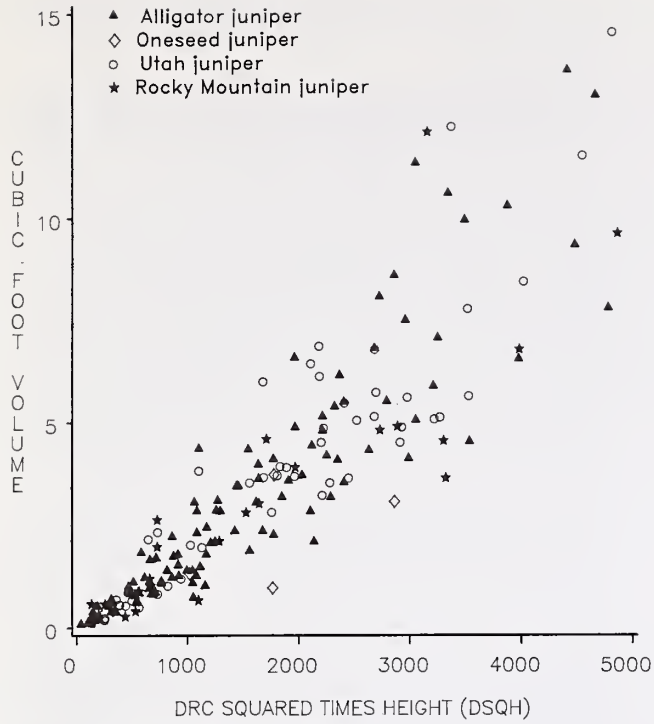

Figure 2—Volume data comparison of juniper species for trees up to 15 to 17 inches DRC.

The two-part volume model was conditioned to be both smooth and continuous at the point where the two equations meet. This was done by imposing two restrictions on the model:

$$\beta_3 = \beta_0 + 3\beta_2 X_0^2 \quad (3)$$

$$\beta_4 = -2\beta_2 X_0^3 \quad (4)$$

The first restriction, equation 3, was obtained by substituting X_0 for X in equation 2 and then equating the two equation parts. The other restriction, equation 4, was obtained by equating the first derivation of the two parts of equation 2 at the point $X = X_0$.

Parameters for the two-part model equation 2 were determined using weighted regression with X raised to the 1.5 power as the weight (Schreuder and Anderson 1984). I did the actual parameter estimation in two steps. Because previously mentioned data problems were suspected, the Cook's D influence statistic was computed for each observation (Cook 1977). The Cook's D-values were arrayed, and from this array the 28 most influential trees in parameter estimation were examined. Most of these trees were found in error and 26 were deleted. A second regression analysis revealed fewer extreme Cook's D-values, and the 26 deleted trees accounted for the outlying extremes from the previous regression analysis. Final parameter estimates were taken from the second regression, as examination of regression statistics and residual plots proved satisfactory.

I recomputed the coefficient of determination from regression (R^2 statistic) for each volume equation from unweighted data for large and small trees. The R^2-statistics averaged for large and small trees were:

Equation category	R^2
Multiple-stem juniper	0.86
Single-stem juniper	.84
Multiple-stem oak	.77
Single-stem oak	.79
Multiple/single-stem pinyon	.93

RESULTS AND DISCUSSION

Estimated volume equation parameters and tabulated volume equation values are given in tables 1, 2, and 3. The range of the data used to construct the equations is outlined in the tables, and numbers of sample trees are summarized in the table margins by DRC and height classes. Note that the multiple-stem volumes for the smallest juniper and oak in tables 1 and 2 are estimated to be zero. Further extrapolation to short 3-inch DRC trees will yield negative volumes in some cases.

Graphical comparison was made among the five equations and between similar Arizona volume equations developed for the Hualapai/Havasupai Indian Reservations (Chojnacky and Ott 1986). There are clear differences among Fort Apache/San Carlos equations (solid lines in fig. 3). For example, the multiple-stem equations show less

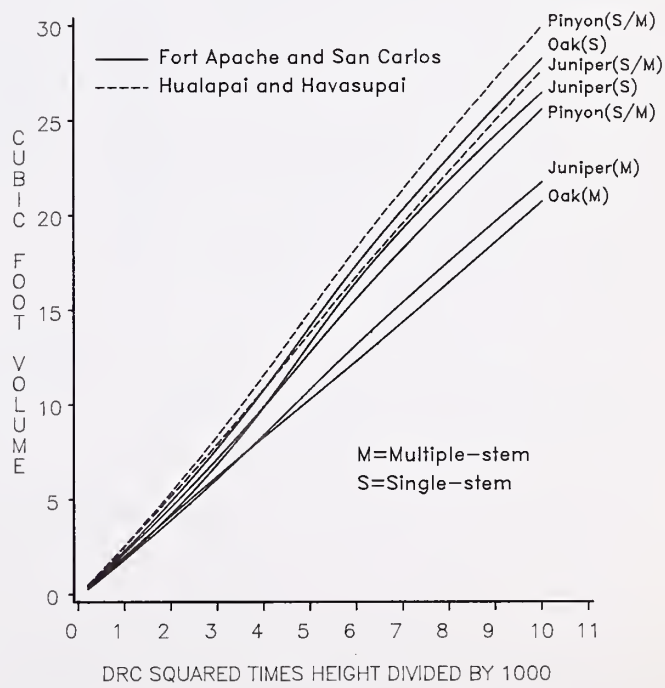

Figure 3—Comparison of Fort Apache/San Carlos volume equations and Hualapai/Havasupai volume equations.

volume than do single-stem equations for trees of similar dimensions. Interestingly, there are smaller differences among species groups than between single-stem and multiple-stem equations.

The Hualapai/Havasupai volume equations were not necessarily expected to be comparable to Fort Apache/San Carlos equations because the two areas are geographically separated by the Mogollon Rim and are more than 200 miles apart. However, the Hualapai/Havasupai juniper equation is similar (in fig. 3) to the Fort Apache/San Carlos single-stem juniper equation. The pinyon equations appear different between the two areas.

Exact interpretation of the differences shown in figure 3 is difficult because of possible data measurement inconsistencies in the Fort Apache/San Carlos data. However, the Fort Apache/San Carlos volume equation predictions appear smaller than do the Hualapai/Havasupai volume equation predictions for trees of a given size. Therefore, the effect, if any, of the data inconsistencies probably did not overinflate Fort Apache/San Carlos volume predictions.

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Table 1—Juniper outside bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet) 6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	45	Number of trees
Inches		*Cubic feet*																	
4	Multiple	0.0	0.1	0.1	0.2	0.3	0.3	0.4	0.5										1
	Single	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6										13
6	Multiple	0.2	0.4	0.5	0.7	0.8	1.0	1.1	1.2	1.4	1.5								5
	Single	0.4	0.5	0.6	0.8	0.9	1.1	1.2	1.3	1.5	1.6								22
8	Multiple	0.6	0.8	1.1	1.3	1.6	1.9	2.1	2.4	2.6	2.9	3.2	3.5	3.7	4.0	4.4	5.1	5.8	12
	Single	0.7	0.9	1.2	1.4	1.7	2.0	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.3	4.8	5.6	6.5	26
10	Multiple		1.4	1.8	2.2	2.6	3.0	3.5	3.9	4.3	4.8	5.2	5.6	6.1	6.5	7.2	8.4	9.6	15
	Single		1.5	1.9	2.3	2.8	3.2	3.7	4.2	4.7	5.2	5.7	6.3	6.8	7.4	8.3	9.8	11.5	20
12	Multiple		2.1	2.7	3.3	3.9	4.5	5.2	5.8	6.5	7.1	7.8	8.5	9.1	9.8	10.9	12.6	14.2	18
	Single		2.2	2.9	3.5	4.2	5.0	5.7	6.5	7.3	8.2	9.0	10.0	10.9	11.9	13.4	15.7	17.9	21
14	Multiple		3.0	3.8	4.7	5.5	6.4	7.3	8.2	9.1	10.1	11.0	12.0	12.9	13.8	15.1	17.2	19.3	14
	Single		3.2	4.1	5.1	6.1	7.2	8.4	9.6	10.9	12.2	13.6	14.9	16.1	17.3	18.9	21.4	23.8	13
16	Multiple		4.0	5.1	6.2	7.4	8.6	9.8	11.1	12.3	13.5	14.6	15.8	16.9	18.0	19.6	22.2	24.8	3
	Single		4.3	5.6	7.0	8.6	10.2	11.9	13.6	15.3	16.9	18.3	19.7	21.0	22.3	24.1	27.0	29.7	6
18	Multiple			6.6	8.1	9.7	11.2	12.8	14.2	15.7	17.1	18.4	19.8	21.1	22.5	24.5	27.7	31.0	4
	Single			7.5	9.5	11.6	13.9	16.0	17.9	19.6	21.3	22.8	24.4	25.8	27.2	29.3	32.6	35.8	7
20	Multiple				10.3	12.2	14.1	15.8	17.5	19.2	20.9	22.5	24.2	25.8	27.4	29.8	33.8	37.7	5
	Single				12.5	15.2	17.6	19.8	21.8	23.7	25.5	27.3	29.0	30.7	32.3	34.7	38.6	42.4	8
22	Multiple				12.7	14.9	17.0	19.1	21.1	23.1	25.0	27.0	28.9	30.8	32.8	35.6	40.4	45.1	3
	Single				15.9	18.7	21.2	23.5	25.7	27.8	29.9	31.9	33.8	35.7	37.6	40.4	44.9	49.4	7
24	Multiple					17.7	20.1	22.5	24.8	27.1	29.5	31.7	34.0	36.3	38.6	41.9	47.6	53.2	2
	Single					22.0	24.7	27.2	29.7	32.0	34.3	36.6	38.8	41.0	43.2	46.4	51.7	56.9	4
26	Multiple							26.1	28.8	31.5	34.2	36.9	39.5	42.2	44.8	48.8	55.4	61.9	0
	Single							31.0	33.7	36.4	39.0	41.6	44.1	46.6	49.1	52.8	58.9	65.0	6
28	Multiple							30.0	33.1	36.2	39.3	42.4	45.5	48.5	51.6	56.1	63.7	71.3	0
	Single							34.9	37.9	40.9	43.9	46.8	49.7	52.5	55.4	59.6	66.6	73.6	2
30	Multiple							34.2	37.7	41.2	44.8	48.3	51.8	55.3	58.8	64.0	72.7	81.4	0
	Single							38.9	42.4	45.7	49.0	52.3	55.6	58.8	62.1	66.9	74.9	82.9	2
32	Multiple								42.6	46.6	50.6	54.5	58.5	62.5	66.5	72.4	82.3	92.2	0
	Single								47.0	50.7	54.5	58.2	61.8	65.5	69.2	74.6	83.7	92.7	4
35	Multiple								50.4	55.2	59.9	64.7	69.4	74.2	78.9	86.0	97.8	109.7	0
	Single								54.3	58.7	63.1	67.5	71.9	76.2	80.6	87.1	97.8	108.6	3
40	Multiple								65.0	71.2	77.4	83.5	89.7	95.9	102.1	111.3	126.8	142.2	1
	Single								67.8	73.5	79.2	84.8	90.4	96.1	101.7	110.1	124.1	138.1	1
45	Multiple										97.1	104.9	112.7	120.5	128.3	140.0	159.5	179.0	0
	Single										97.1	104.2	111.3	118.4	125.5	136.1	153.8	171.5	0
Number of trees		2	3	7	30	36	51	27	29	17	15	14	4	4	1	2	4	2	248

Multiple stem:

$$\text{Volume} = \begin{cases} -0.169 + 1.9246 \cdot X + 0.0530 \cdot X^2 & \text{for } X \le 5 \\ 3.805 + 1.9246 \cdot X - 13.249/X & \text{for } X > 5 \end{cases}$$

Single stem:

$$\text{Volume} = \begin{cases} -0.002 + 1.7385 \cdot X + 0.1810 \cdot X^2 & \text{for } X \le 5 \\ 13.572 + 1.7385 \cdot X - 45.246/X & \text{for } X > 5 \end{cases}$$

where: X = DRC • DRC • Height/1,000

Table 2—Oak outside bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet) 6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	Number of trees
Inches		Cubic feet																
4	Multiple	0.0	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.7	0.8	0.9	0.9			0
	Single	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.1			12
6	Multiple	0.3	0.4	0.6	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.9	2.0	2.2	2.3			13
	Single	0.5	0.6	0.8	0.9	1.1	1.3	1.5	1.6	1.8	2.0	2.1	2.3	2.5	2.7			28
8	Multiple	0.7	0.9	1.2	1.5	1.8	2.0	2.3	2.6	2.9	3.1	3.4	3.7	4.0	4.2	4.6	5.3	16
	Single	0.8	1.1	1.4	1.7	2.0	2.4	2.7	3.0	3.3	3.6	4.0	4.3	4.7	5.0	5.5	6.4	23
10	Multiple	1.1	1.6	2.0	2.4	2.8	3.3	3.7	4.1	4.5	5.0	5.4	5.8	6.2	6.6	7.2	8.3	21
	Single	1.3	1.8	2.3	2.8	3.3	3.8	4.3	4.9	5.4	6.0	6.5	7.1	7.7	8.3	9.2	10.8	11
12	Multiple	1.7	2.3	2.9	3.5	4.2	4.8	5.4	6.0	6.6	7.1	7.7	8.3	8.9	9.5	10.3	11.8	16
	Single	2.0	2.7	3.4	4.1	4.9	5.7	6.5	7.3	8.2	9.1	10.0	10.9	11.8	12.8	14.2	16.6	10
14	Multiple		3.2	4.0	4.9	5.7	6.5	7.3	8.1	8.9	9.7	10.4	11.2	12.0	12.8	14.1	16.1	13
	Single		3.7	4.8	5.8	6.9	8.1	9.3	10.5	11.8	13.1	14.4	15.7	17.0	18.2	19.9	22.6	7
16	Multiple		4.2	5.3	6.4	7.4	8.4	9.5	10.5	11.5	12.6	13.6	14.7	15.8	16.8	18.5	21.2	6
	Single		5.0	6.4	7.9	9.5	11.1	12.8	14.5	16.2	17.8	19.3	20.8	22.2	23.6	25.6	28.8	5
18	Multiple			6.7	8.0	9.3	10.6	11.9	13.3	14.6	16.0	17.3	18.7	20.1	21.5	23.6	27.1	6
	Single			8.4	10.4	12.5	14.7	16.8	18.8	20.7	22.4	24.2	25.9	27.5	29.1	31.5	35.4	4
20	Multiple				9.9	11.5	13.1	14.8	16.4	18.1	19.8	21.6	23.3	25.0	26.7	29.3	33.7	2
	Single				13.4	16.1	18.6	20.9	23.1	25.2	27.2	29.2	31.2	33.1	35.0	37.9	42.6	4
22	Multiple						15.9	17.9	20.0	22.1	24.2	26.3	28.3	30.4	32.5	35.7	41.0	1
	Single						22.4	24.9	27.4	29.8	32.2	34.5	36.8	39.1	41.4	44.7	50.3	0
24	Multiple						19.0	21.5	24.0	26.4	28.9	31.4	33.9	36.4	38.9	42.7	49.0	2
	Single						26.2	29.1	32.0	34.7	37.5	40.2	42.8	45.5	48.1	52.1	58.6	3
26	Multiple						22.4	25.4	28.3	31.2	34.1	37.1	40.0	43.0	45.9	50.3	57.7	0
	Single						30.3	33.5	36.8	39.9	43.1	46.2	49.3	52.3	55.4	60.0	67.5	4
28	Multiple						26.2	29.6	33.0	36.4	39.8	43.2	46.6	50.0	53.5	58.6	67.2	0
	Single						34.4	38.2	41.8	45.4	49.0	52.6	56.1	59.7	63.2	68.4	77.2	0
30	Multiple						30.2	34.1	38.0	41.9	45.8	49.8	53.7	57.6	61.6	67.5	77.3	0
	Single						38.8	43.0	47.2	51.3	55.3	59.4	63.4	67.4	71.5	77.5	87.4	1
32	Multiple						34.5	38.9	43.4	47.9	52.3	56.8	61.3	65.8	70.2	77.0	88.2	0
	Single						43.4	48.1	52.8	57.4	62.0	66.6	71.2	75.7	80.3	87.1	98.4	0
Number of trees		3	8	25	33	28	36	23	21	11	7	4	1	3	0	5	0	208

Multiple stem:

$$\text{Volume} = \begin{cases} -0.181 + 2.1917 \cdot X - 0.0208 \cdot X^2 & \text{for } X \leq 5 \\ -1.742 + 2.1917 \cdot X + 5.205/X & \text{for } X > 5 \end{cases}$$

Single stem:

$$\text{Volume} = \begin{cases} -0.020 + 2.1896 \cdot X + 0.1270 \cdot X^2 & \text{for } X \leq 5 \\ 9.502 + 2.1896 \cdot X - 31.740/X & \text{for } X > 5 \end{cases}$$

where: X = DRC • DRC • Height/1,000

Table 3—Pinyon outside bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet) 6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	Number of trees
Inches		*Cubic feet*																
4	Single/ Multiple	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.8						20
6	Single/ Multiple	0.4	0.6	0.7	0.9	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.2					18
8	Single/ Multiple			1.3	1.6	1.9	2.2	2.5	2.8	3.1	3.4	3.7	4.1	4.4				8
10	Single/ Multiple			2.2	2.6	3.1	3.6	4.1	4.6	5.1	5.6	6.1	6.6	7.1	7.7	8.5	9.9	19
12	Single/ Multiple				3.9	4.6	5.3	6.1	6.8	7.6	8.4	9.1	9.9	10.8	11.6	12.9	14.9	12
14	Single/ Multiple					6.5	7.5	8.6	9.6	10.7	11.9	13.0	14.2	15.2	16.3	17.9	20.3	4
16	Single/ Multiple						10.1	11.6	13.1	14.6	16.0	17.3	18.6	19.9	21.2	23.1	26.1	1
18	Single/ Multiple						13.3	15.1	16.9	18.5	20.2	21.8	23.3	24.9	26.4	28.7	32.4	0
20	Single/ Multiple							18.7	20.7	22.7	24.6	26.5	28.4	30.2	32.0	34.8	39.3	0
22	Single/ Multiple							22.5	24.8	27.1	29.3	31.6	33.8	36.0	38.1	41.4	46.8	2
24	Single/ Multiple								29.1	31.8	34.4	37.0	39.6	42.1	44.7	48.5	54.9	0
26	Single/ Multiple								33.7	36.7	39.8	42.8	45.8	48.8	51.8	56.2	63.6	0
Number of trees		0	0	7	8	4	12	8	10	9	4	10	7	2	0	3	0	84

$$\text{Volume} = \begin{cases} -0.073 + 2.1608 \cdot X + 0.0804 \cdot X^2 & \text{for } X \leq 5 \\ 5.961 + 2.1608 \cdot X - 20.112/X & \text{for } X > 5 \end{cases}$$

where: X = DRC • DRC • Height/1,000

INTERMOUNTAIN RESEARCH STATION

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